# CRYOGENIC FLUID MANAGEMENT PORTFOLIO PROJECT (CFMPP)

## Project Update for the NASA Advisory Council (NAC)

## Technology, Innovation and Engineering (T&IE) Committee


**Lauren M. Ameen**

Deputy Project Manager

NASA Glenn Research Center


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# CFM Portfolio Project (CFMPP)

- *Project Objective:* **Mature CFM technologies essential to NASA's future missions in science and exploration which utilize both chemical and nuclear in-space propulsion, landers, and in-situ resource utilization**
- **Space Technology Mission Directorate (STMD) portfolio project comprised of over twenty individual CFM technology development activities**
  - Includes non-flight demo activities related to Lunar/Mars surface system applications (ex. ISRU liquefaction)
- **Partnered leadership and execution by NASA's Marshall Spaceflight Center and Glenn Research Center**
  - MSFC PM: Jeremy Kenny; GRC Deputy PM: Lauren Ameen
- **CFMPP aims to close technology gaps, with focus on integrated CFM systems development and demonstration, to advance the national goals of landing on the Moon and Mars**
- **Technology entrance minimum of TRL 4, with project end state objective of TRL 7 (Flight Demonstration)**
  - CFMPP has developed and implemented a rigorous TRL assessment and advancement process
- **CFMPP leverages Agency-wide mission developments and expertise for prioritization of activities**

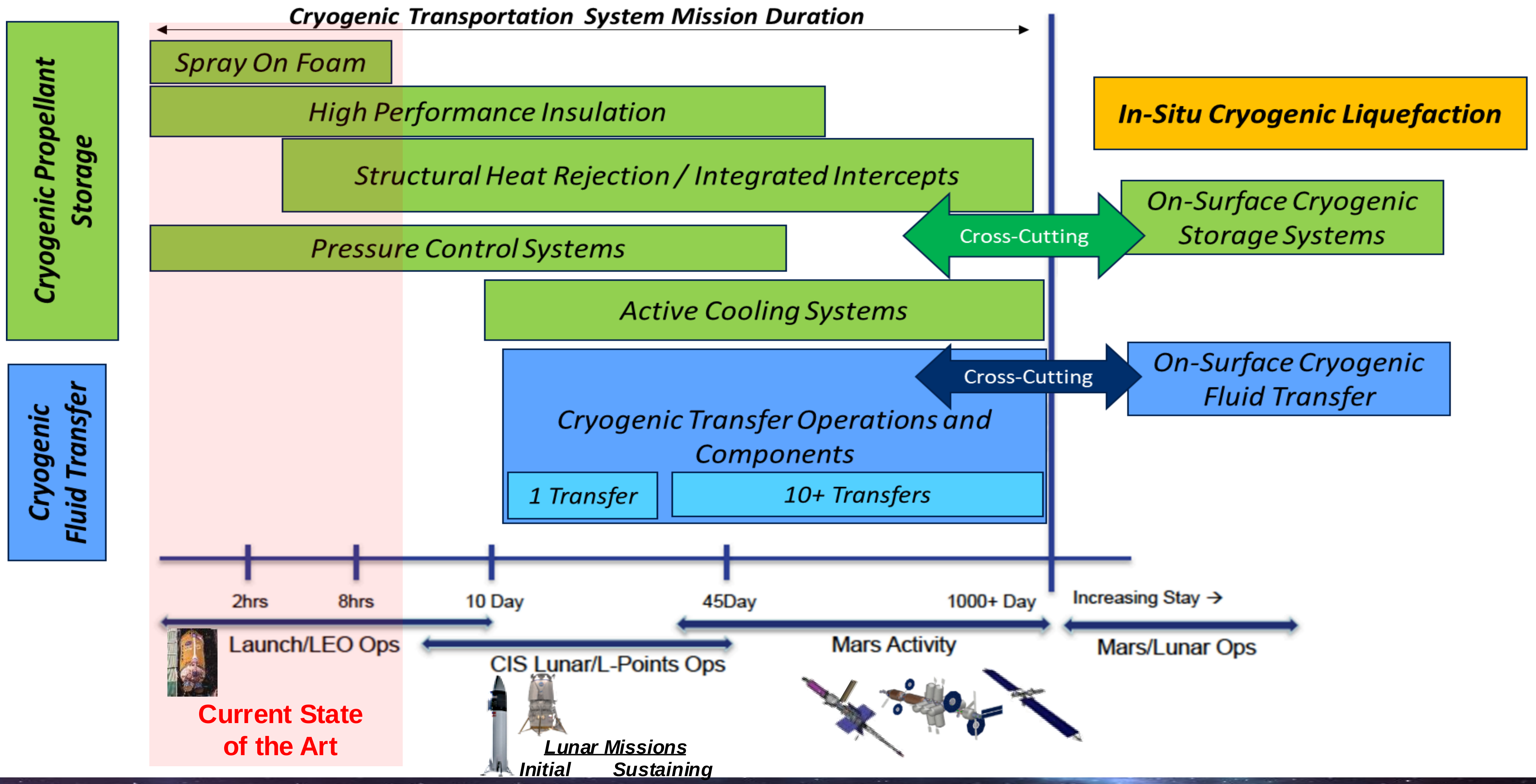
***To mature CFM technologies critical for space flight applications, CFM flight demonstrations are required. Flight demonstrations must be of appropriate scale, utilize integrated systems, and be performed in extended microgravity and thermal environments***

# Cryogenic Fluid Management Technology Pulls

*Photo Credit: NASA*

- **Interest for cryogenic propulsion systems is nearing an all-time high across both the government and industry**
- **Moon to Mars will push cryogenic mission durations from months to years**
- **Enabling CFM technologies at TRL ≥ 6 for Mars and Cis-lunar transportation, ISRU, and Surface Systems operations are required for the Moon to Mars Campaign**
  - Advanced cryogenic propellant storage and transfer integrated systems, operable in microgravity environments, are required for **all** proposed mission architectures
- **Increasing cryogenic mission duration drives the need for more advanced CFM technology**
  - Current CFM capabilities support missions on the order of days

# CFM Technology Capability Needs



# Cryogenic Fluid Management Portfolio Project (CFMPP)

CRYOGENIC FLUID MANAGEMENT PORTFOLIO PROJECT

System Demonstration Complexity →

## Technologies Portfolio

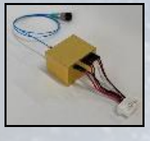
***Scope:*** Design, development, testing, and evaluation of critical-need cryogenic components enabling long-duration CFM storage and propellant transfer

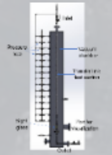
**Major Activities:**

Hydrogen low-leakage valves and cryo-couplers

Radio Frequency Mass Gauge (RFMG)

Next-generation FOSS (fiber optics sensing system)





Reduced Gravity Cryogenic Transfer (RGCT)

## Subsystems Portfolio

***Scope:*** Design, development, and testing of complex systems of technologies to address technical challenges for specific CFM mission needs

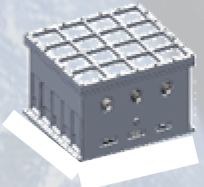
**Major Activities:**

20W/20K Cryocooler

150W/90K Cryocooler

Cryocooler Electronics

Alternate Cryocooler Studies



Images by Creare LLC

## Demonstrations Portfolio

***Scope:*** Design, build, and test integrated flight and ground systems comprised of multiple CFM subsystems, enabling TRL 5+ maturation for many technologies

**Major Activities:**

Tipping Point Demo Contracts

Ground System Demonstrations

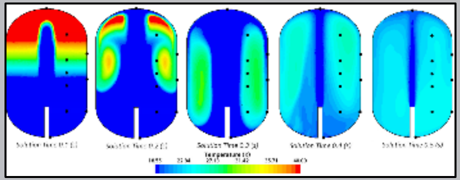
Two-Stage Cooling Demonstration

CryoFILL Liquefaction Demonstration

## Modeling Portfolio

***Scope:*** Develop, enhance, validate, and demonstrate Computational Fluid Dynamics (CFD) and Nodal tools to address capability gaps for predicting cryogenic fluid behavior in 1-G and microgravity environments for use as design tools for future NASA missions

Testing and demo activities across the CFMP portfolio used within modeling tools to predict CFM behavior at a flight vehicle scale in a relevant microgravity environment



System Validation →

# 2020 Tipping Points – ULA



## Cryogenic (H2/O2) Smart Propulsion Flight Demonstration

Overview:  Flight demonstration of key CFM technologies:

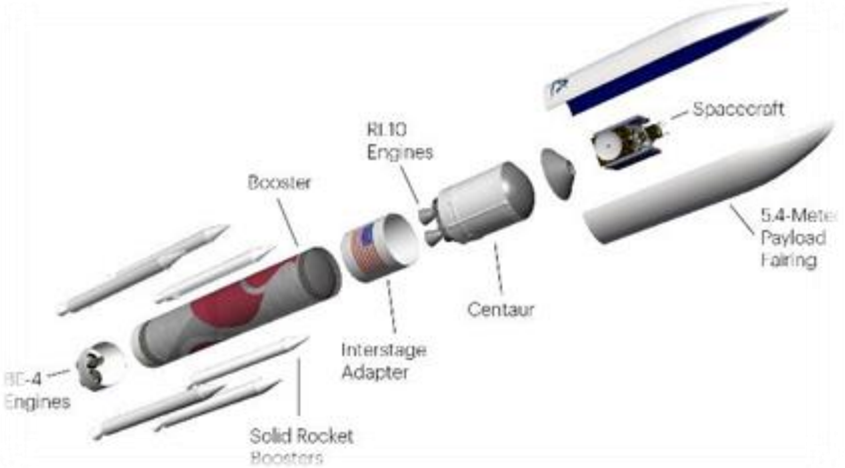
- passive thermal control,
- tank pressure control,
- tank-to-tank propellant transfer

Mission Overview:

- ULA will utilize Vulcan flight ‘rideshares’ to execute the demonstration objectives; flights to occur post Certification -1 mission
- Demonstration occurs after primary spacecraft is separated; ULA will fly the Tipping Point LEAP hardware system as an integrated propulsion subsystem interfaced with the Centaur V propellant tanks; low earth orbit insertion for demonstration mission
- ~1 day on-orbit duration per mission

Program Accomplishments: Completed Critical Design Phase, actively working Assembly Integration & Test

Projected Flight:  2025




ULA Vulcan ‘Certification-1’ Launch

# 2020 Tipping Points – Eta Space

Liquid Oxygen Flight Demonstration (LOXSAT-1)

Overview: Develop, launch and fly a technology demonstration payload designed to test multiple CFM technologies necessary for creating practical propellent depots.

Mission Overview:

- Flight demonstration based on:
  - Zero fluid loss storage in LEO environment
  - Control of fluid position and thermodynamic state
  - Control of tank pressure using autogenous and helium pressurization
  - Tank-to-tank fluid transfer
- LOXSAT-1 hosted on a dedicated Rocket Lab Photon satellite bus and launched on a Rocket Lab Electron launch vehicle
- ≤ 9-month mission

Program Accomplishments: Completed Critical Design Phase, in Assembly Integration & Test

Projected Flight: 2025

# 2020 Tipping Points - SpaceX

On-Orbit Large-Scale Cryogenic Propellant Management and Transfer Demonstration

Overview: Demonstration of large-scale on-orbit cryogenic fluid transfer of liquid oxygen (up to 3 metric tons) between tanks on a Starship in orbit and management to provide a basis for operational use of in-space refueling technology.

Mission Overview:

- Demonstration conducted as part of a Starship flight
- Active settling maneuver with settled transfer between propellant tanks located within Starship (*not ship-to-ship*)
  - Flight-3 included special demonstration hardware specific to Tipping Point
- ≤ 1 day mission duration

**Flight Demonstration Completed on Starship Flight-3 on March 14, 2024!**

- Conducted the large-scale propellant transfer, moving several metric tons of propellant from one tank to another, while in space
- Storing and transferring cryogenic propellant in orbit has never been attempted on this scale before. This is a huge milestone toward providing NASA with the technologies it will need for both a long-term presence on the moon and its boldest missions to deep space destinations such as Mars and beyond.


# Successful RFMG Demo on CLPS IM-1

**Radio Frequency Mass Gauge (RFMG) Technology**

Measures tank RF spectrum to provide tank fill level; the spectrum changes with fill level, since the dielectric fluid (e) slows the speed of light

- Tech has been in development for over 15 years at Glenn Research Center

**RFMG successfully *flew and operated* onboard the Intuitive Machines IM-1 Nova-C (Odysseus) lunar lander as part of Commercial Lunar Payload Services Program!**

- Mission Objectives:
  - Support pre-flight and flight operations during CLPS Program with Intuitive Machines (IM-1) Nova C lander.
  - Demonstrate RFMG system operations at multiple fluid levels for both liquid oxygen (LOX) and liquid methane (LCH4) propulsion tanks throughout IM-1 mission.
- NASA team participated multiple in pre-launch activities, including RF fluid simulations and propellant tanking during wet-dress rehearsals

**This technology was actively used on throughout IM-1 mission, where it not only provided critical data to advance the RFMG technology but also assisted the IM-1 team during maneuvers and the lunar landing.**

*Propellant loading of IM-1 tank at LC 39A*


*NASA RFMG Mission Operations Team*

*Credit: Intuitive Machines*

# Low-Leakage Hydrogen Valves

**NASA team at Marshall Space Flight Center has developed a *patented* valve technology that utilizes a seat and poppet concept enabling self-alignment, greatly reducing leakage rates.**

- **Activity Goal:**
  - Develop valves that are more tolerant of imperfections and reduce internal leakage rates by an order of. Traditional internal leakage rates up to 2000 Standard Cubic Inches per Minute (SCIM)
  - Low-leakage rates are required for future long-duration cryogenic missions
- **In 2023, CFMPP team successfully developed and tested a relief valve design on small scale at MSFC**
  - Test results indicated leakage rates under 1.0 SCIM
  - Achieved TRL 4 criteria
- **CFMPP started new activity in 2024 to continue valve technology development and begin tech transfer and infusion with industry**
  - Procure a high-fidelity prototype valve from a commercial partner which will enable a future test campaign to bring the low-leakage valve design to TRL 6 with the exception of the electromechanical actuator
  - *Contract(s) starting in October 2024*

*Seat Seal Test Fixture*

*Valve Seat Materials*

*Low-leakage relief valve during LH2 testing*

# High-Efficiency Cryocoolers

## 90K/150W Reverse Turbo-Brayton (RTB) Cryocoooler

Phase III SBIR – Creare, LLC

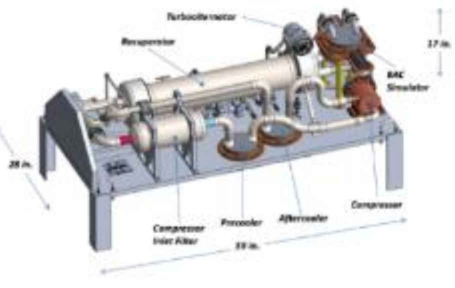
High-capacity 90K cryocoolers are enabling for liquefaction and zero boil-off of LOX and LCH4 and enhancing for zero boil-off of hydrogen for landers and in-space transportation stages.

**Objective:**

- Design, build, and demonstrate a 90K/150W RTB cryocooler having a specific mass of 0.4 kg/W and a specific power requirement of 8.0 W/W
- Activity exit goal: **TRL 6**

**Accomplishments:**

- All three components (Compressor, Recuperator, and Turbo-Alternator) integrated in Engineering Model unit and verified performance
  - **TRL 5 Achieved!**
- Perform vibration testing on EM and repeat functional testing




**150W/ 90K Cryocooler Design**

**Delivery to NASA in 2024**

## 20K/20W Reverse Turbo-Brayton (RTB) Cryocoooler

Phase III SBIR – Creare, LLC

20K-class cryocoolers enable the capability of zero boil-off storage of LH2, which is critical to long-duration LH2-based architectures for exploration.

**Objective:**

- Design, build, and demonstrate a 20W 20K/20 RTB cryocooler with a specific mass of 4.4 kg/W and a specific power requirement of 60 W/W
- Activity exit goal: **TRL 6**

**Accomplishments:**

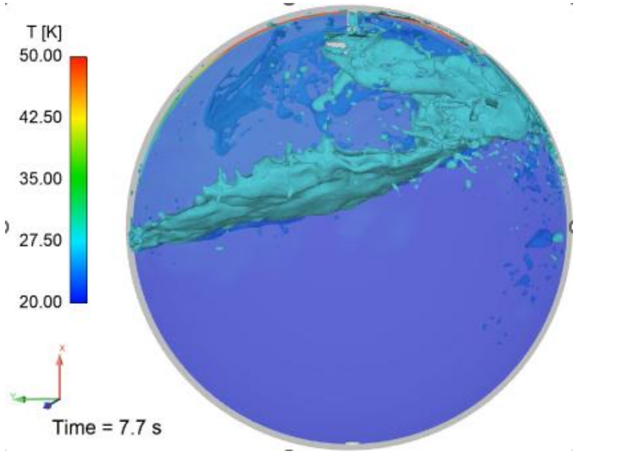
- Successfully completed preliminary thermodynamic performance testing
  - **TRL 5 Achieved!**

**20W 20K Cryocooler in Cleanroom**

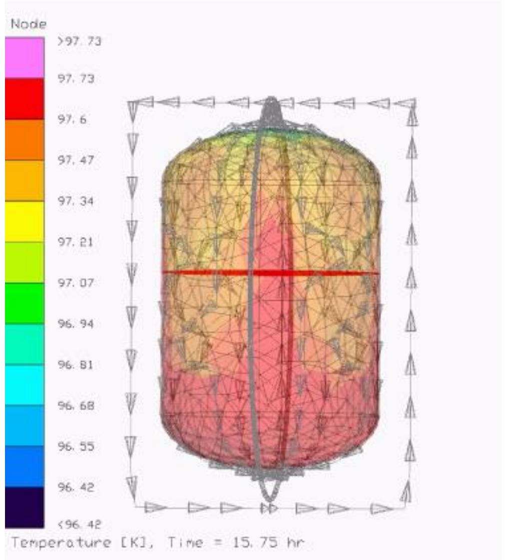
**Delivery to NASA in 2025**

# Cryogenic Fluid Modeling

- **NASA has spent the past 20 years developing and validating multi-node and CFD (Computational Fluid Dynamics) modeling tools for cryogenic propellant applications**
- **Current CFM Modeling Portfolio supports stakeholders through development and validation of pre-predictive models against cryogenic experimental data**
- **CFM Modeling Team uses experimental ground and flight data to model cryogenic fluid phenomena**
  - Quality of modeling is dependent on the quality of the experimental data; flight demonstrations which are expensive and rare
  - With more confident models, systems can be designed with reduced margin and greater performance.
- **Modeling will be complete when the CFM risks are acceptable to the project/stakeholders, with definition of success actively in dialogue across the Agency**
- ***Multiple occurrences of industry modeling tool infusion/transfer and knowledge sharing with Industry Partners***



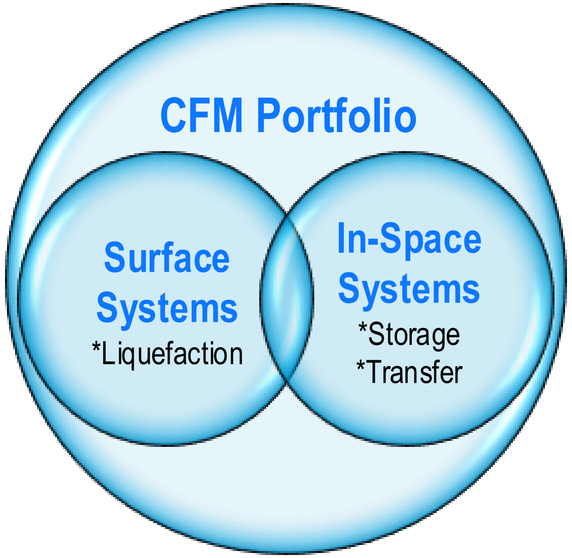

CFD Tank Propellant Slosh Analysis




Nodal Liquefaction Analysis

# Capability Shortfalls

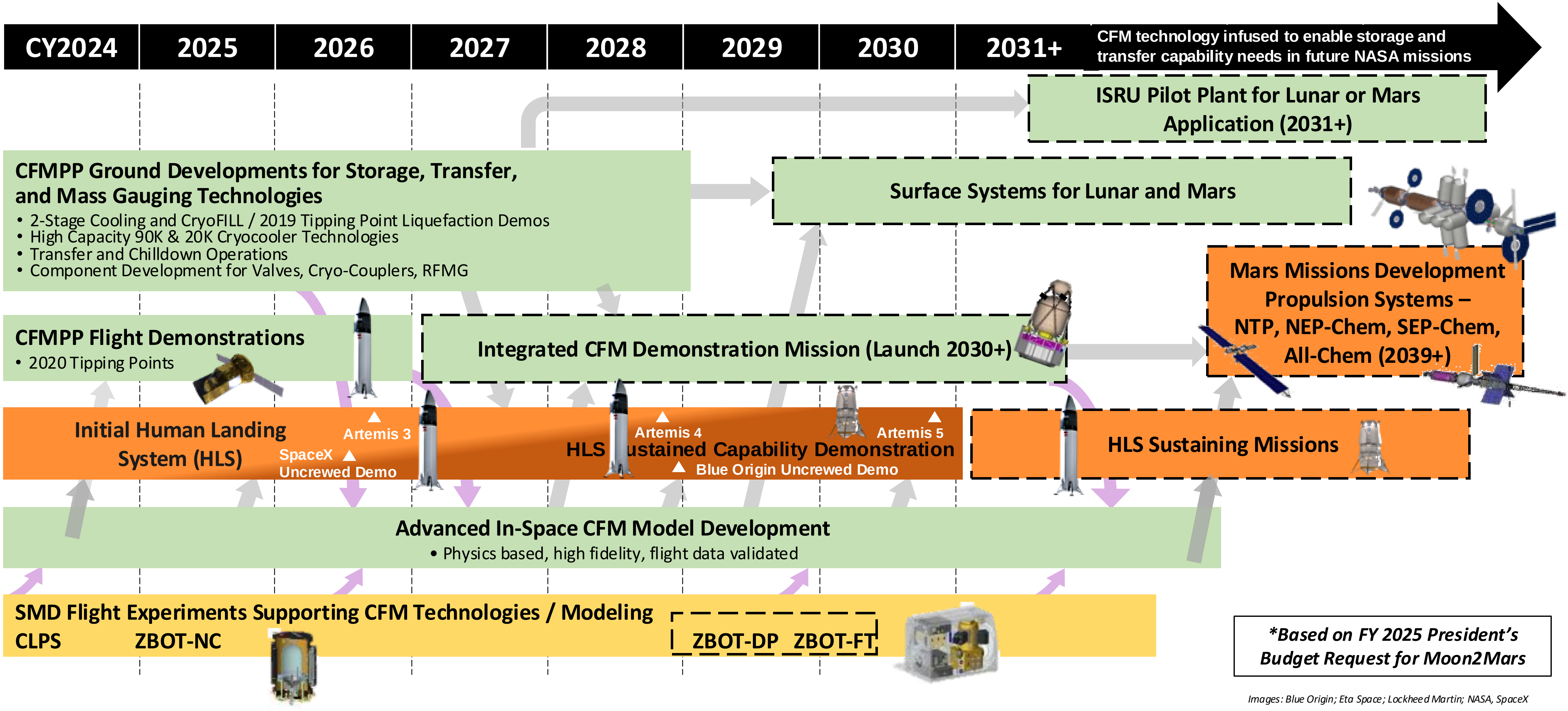
- **Numerous CFM capability shortfalls exist for both in-space transportation and Lunar/Mars surface system applications. Priority areas aligned with the STMD CFM Shortfalls**
  - Cryogenic Propellant Storage (#17 of 187)
  - Cryogenic Fluid Transfer (#21 of 187)
  - In-Situ Cryogenic Liquefaction
  - Cryogenic Fluid Management Predictive Modeling
  - Cross Discipline Cryogenic Fluid Management




- **Since 2021, CFMPP has assessed the potential for gravity-dependent shortfall closure via:**
  1. Assessment of all cryogenic missions currently in-scope across the Agency architecture (ex. HLS)
  2. In-house development of a Government Reference Integrated CFM Demo Mission

- **CFMPP has integrated with Agency Stakeholders (ESDMD, SMD, ARMD) on evolving mission objectives and architectures; shortfalls being revised based on Stakeholder feedback**

# CFM Notional Near-Term Roadmap*




*Last Updated:* August 19, 2024

STMD | ESDMD | SMD | Pre-Formulation

**Arrows indicate cross-project/program integration**

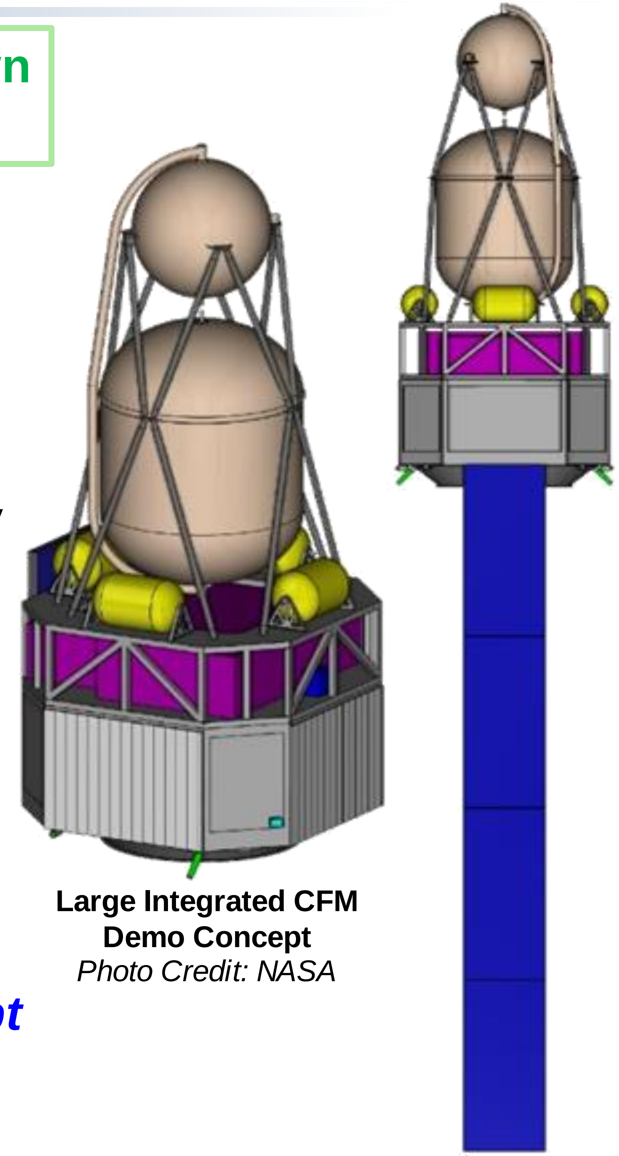
Curved – delivery of data for model development/validation

Straight - technology and validated models infused to enabling system development

# CFMPP Approach for Integrated Flight Demonstration

**Integrated system-level microgravity flight demo must be conducted to buy-down technical risk (increase TRL) for future long-duration cryogenic missions**

- **CFMPP has been developing the gov't reference concept mission and requirements supporting remaining technology shortfall closure**
  - Mission pull need in the mid-2030s, with intent to build-upon cislunar CFM advancements
- **Demo concept defines appropriate scale and operational duration required to provide sufficient data enabling TRL 6+ maturation**
  - CFMPP has baselined LH2 cryogen for demonstration → maximized cross-cutting technology gap closure to LO2/LCH4 systems
- **Concept Highlights:**
  - Large $LH_2$ Flight Demonstrator, Class D Mission
  - Mission lasts up to 8 months, providing flight data critical for design model validation
  - Integrated cryogenic demo mission phases will include:
    - Cryogenic active and passive storage operations
    - Cryogenic transfer system operations
- ***CFMPP will continue Pre-Formulation of Government reference mission concept scope in FY25 while establishing budget baseline with STMD***



**Large Integrated CFM Demo Concept**
*Photo Credit: NASA*

# Summary and Forward Work

- **NASA through CFMPP is seeking and leveraging infusion opportunities to advance US goals of landing on the Moon and Mars**
- **CFMPP is refining CFM Capability goals and development roadmaps to maintain Portfolio strategic alignment with stakeholders**
- **Forward work includes:**
  – Initiating industry acquisition approaches for key activities
    - Cryocooler industry base expansion, low leakage valve contracts
  – Pursuit of potential mission partnerships (e.g., ESDMD, ARMD)
  – Refining Integrated CFM Flight Demonstration mission reference concept to establish CFM flight demonstration requirements
    - Reference concept closes priority CFM shortfall gaps and addresses stakeholder cryogenic system critical development needs
    - Reference concept demonstration requirements used to identify other mission opportunities

**Integrated CFM Flight Demo Concept**
*Photo Credit: NASA*